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Technical review of wind energy potential as small-scale power generation sources in Penang Island Malaysia

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ABSTRACT

This project presents an investigation and assessment of the wind energy potential in Penang Island, located about 15 km off the west (W) coast of Peninsular Malaysia. The wind data were statistically analyzed using Rayleigh distribution function. Based on the investigation, the results show that the measurement site falls under Class 1 of the International System Wind Classification. The climate in Penang Island is highly influenced by the northeast (NE) and southwest (SW) monsoon seasons. Besides that, most of the wind is the prevailing wind from the north (N) and SW directions. Meanwhile, the directions that contribute higher energy frequency are from NE and south-southwest (SSW). The mean annual wind power density (WPD) in this regime is estimated to be about 24.54 W m^{-2}. Furthermore, the mean annual wind energy density (WED) is also forecast to be 17.98 kWh m^{-2} month^{-1}. The total annual WED is 216 kWh m^{-2} year^{-1}. Thus, the results of this investigation indicate that the grid-network connected to the wind turbine-generator systems may not be a commercially viable proposal in Penang. Nevertheless, a small-scale wind turbine system is more suitable and sustainable in Penang Island.

Contents

1. Introduction

Global energy consumption in the last half century has increased rapidly and is expected to continue to grow over the next 50 years. Of the total primary energy demand, the fossil fuels that provide the energy are oil, coal and natural gas. However, the use of fossil fuels will certainly increase worldwide carbon dioxide (CO_2) emissions, and further increase global warming [1]. The global warming is already causing the polar ice caps to melt and it is inevitable that the sea level will increase resulting in less land use for an increasing world population, along with changes in climate. As a result, the depletion of fossil fuel reserves and the need to fulfill an increasing global energy demand have accelerated the efforts to seek alternative fuel sources such as wind power, water power, solar

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Nomenclature

c	scale factor ($\mathrm{m\,s^{-1}}$)
CDF	cumulative density function
CO_2	carbon dioxide
d	number of days in a month (day)
E	east
ENE	east-northeast
ESE	east-southeast
g	gravitation acceleration ($\mathrm{m\,s^{-2}}$)
k	Weibull shape factor
n	total number of wind-speed reading
N	north
NNE	north-northeast
NE	northeast
NW	northwest
NNW	north-northwest
p	pressure (Pa)
PDF	probability density function
P_V	power available in the wind stream for a unit area of rotor ($\mathrm{W\,m^{-2}}$)
R	gas constant (8.314 $\mathrm{J\,K^{-1}\,mol^{-1}}$)
SE	Southeast
SSE	South-southeast
S	South
SSW	South-southwest
SW	Southwest
T	temperature (K)
T_0	standard room temperature, 298 K
t	time duration (s)
V	velocity of wind ($\mathrm{m\,s^{-1}}$)
V_f	the most frequent wind-speed ($\mathrm{m\,s^{-1}}$)
V_m	average wind-speed of a regime ($\mathrm{m\,s^{-1}}$)
V_x	wind velocity to be exceeded ($\mathrm{m\,s^{-1}}$)
v_1	measured wind-speed at z_1 ($\mathrm{m\,s^{-1}}$)
v_2	extrapolated wind-speed at z_2 ($\mathrm{m\,s^{-1}}$)
WED	wind energy density ($\mathrm{kWh\,m^{-2}\,month^{-1}}$)
WPD	wind power density ($\mathrm{W\,m^{-2}}$)
WPD_{act}	actual wind power density ($\mathrm{W\,m^{-2}}$)
WPD_{ray}	wind power density based on Rayleigh distribution ($\mathrm{W\,m^{-2}}$)
WSW	west-southwest
W	west
WNW	west-northwest
z	altitude above sea level (m)
z_1	altitude of a reference height (m)
z_2	altitude of a estimated height (m)

Greek symbols

α	power law exponent
ρ	air density ($\mathrm{kg\,m^{-3}}$)
ρ_0	standard sea level air density ($\mathrm{kg\,m^{-3}}$)
Γ	vertical temperature gradient ($\mathrm{K\,m^{-1}}$)

energy, liquid biofuel, solid biomass, biogas and geothermal energy [2].

Many countries worldwide recognize that the current energy trends are not sustainable and that a better balance must be found among energy preservation, economic development and protection of the environment [3] especially in Malaysia. One of these sources is wind energy. The global wind energy market among other renewable sources has been experiencing a rapid growth especially during the last two decades [4]. Wind is a fuel-free, inexhaustible energy source and does not cause pollution in electricity production. Wind energy helps decreasing import to a sustainable development in many countries [5]. Meanwhile, Malaysia possess high wind energy potential, however, the exploitation and feasibility study of the clean and sustainable renewable energy is still insufficient.

In Malaysia, there are many amenities for wind resources. Malaysia comprises Peninsular Malaysia, Sabah, and Sarawak which lies between the latitudes 1°N and 7°N and also between the longitudes 100°E and 120°E. Malaysia is located in the equatorial zone and the climate is governed by the NE and SW monsoon which blow alternately during the course of the year. The NE monsoon blow from approximately October until March, while the SW monsoon blow from May until September [6]. Due to the country's location, winds over the area are generally light.

In the paper by Sopian et al. [7], the wind data were collected at ten stations in Malaysia had been analyzed for wind energy potential. The stations are located at Mersing, Kuala Terengganu, Alor Setar, Petaling Jaya, Cameron Highlands, Melaka, Kota Kinabalu, Tawau, Labuan, and Kuching. The data were collected over a ten-year period from 1982 till 1991. The results were represented as a Weibull distribution function. Based on the analyses, the station at Mersing has the greatest wind power potential, with a mean annual WPD of 85.61 $\mathrm{W\,m^{-2}}$ and at 10 m above sea level.

Besides that, a case study of the wind energy potential at Pulau Perhentian (Perhentian Island) has also been carried out. Pulau Perhentian is one of the popular resort islands in Malaysia which consists of a cluster of islands off the East (E) coast of Malaysia which is about 21 km from the coast of Terengganu. In the study, a hybrid system integrated with a wind turbine and solar panel had been installed so as to minimize the use of diesel as a source of electricity in Pulau Perhentian [8].

Moreover, Mostafaeripour stated that wind speed frequency distribution has been represented by difference probability density function (PDF) such as Weibull, Rayleigh, three parameter beta, lognormal, and gamma distributions [9]. Besides that, the sum lognormal model has also been used in analyzing the wind distribution which is found to be a good fit as indicated in [10]. Furthermore, the wind-speed measurements at the Materials and Energy Research Centre (MERC) solar site were used to find out the WED and other wind characteristics with the help of the Weibull PDF. The study also emphasized that the Weibull and Rayleigh distribution functions are useful tools for WED estimation but they are not quite appropriate for properly matching the actual wind data of low-mean speeds and short-time records [11,12]. However, Weibull distribution is one of the most commonly used methods for determining wind energy potential [9].

In addition, the research of Zaharim et al. [13] also summarized that the numerical and graphical results obtained from the Weibull and Gamma distributions, which parameters are estimated using the maximum likelihood principle, provide the best fits for the wind data.

Thus, in order to assess the wind potential in Bayan Lepas, Penang Island, the authors were set to use real-time wind data. Within the investigation, the wind-speed, the prevailing direction, the duration and the diurnal variation were assessed, and the wind data were statistically fitted with a Rayleigh distribution function which consists of PDF and cumulative density function (CDF).

2. Methodology

2.1. Site description, measurement mast and wind data

Penang Island, with its capital, Georgetown is located at latitude 5°18′N and longitude 100°16′E, is one of the popular resort islands in Malaysia which is situated about 15 km off the west coast

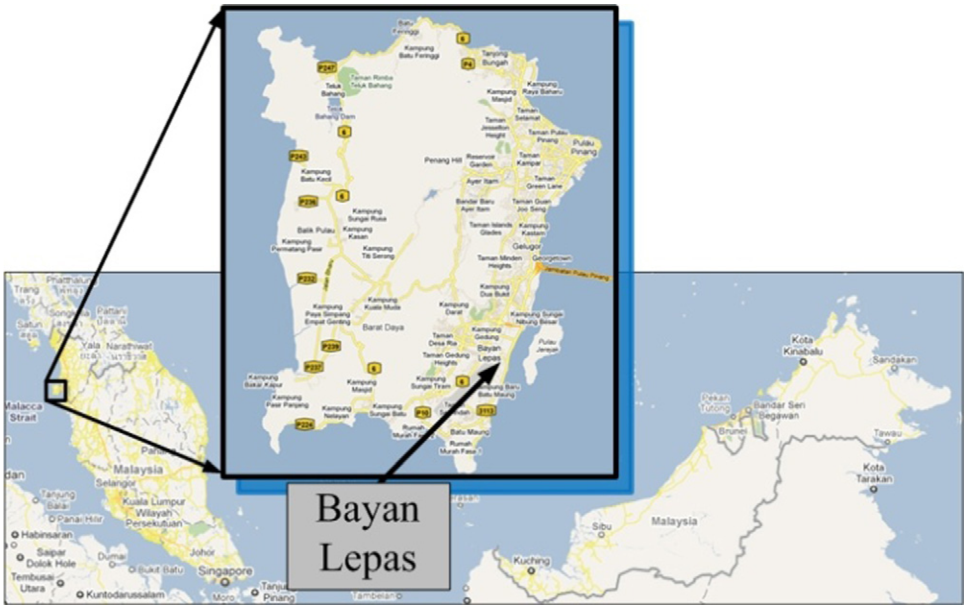

Fig. 1. Measurement site at Bayan Lepas, Penang Island.

of Peninsular Malaysia. The population in this island is 1.58 million people in year 2009 [14]. Besides that, according to the Energy Commission [15], the power generation capacity connected to the Malaysian National Grid is 19,723 MW, meanwhile, a maximum demand of 14,007 MW was recorded. In the Performance and Statistical Information 2008 [15], the total electricity generation is 113,823 GWh with total electricity consumption as 99,548 GWh as well as the per capita electricity consumption is 3594 kWh. Furthermore, the generation mix of electricity by type of fuel in Malaysia is 62.8% gas, 27.3% coal, 6.9% hydro and 3% for others [15]. Since Penang Island is surrounded by the Sea, there may be plenty of wind resources available especially at the offshore location.

The wind data collected from the meteorological station is located at Bayan Lepas as shown in Fig. 1. The wind measuring instruments are the cup anemometer and wind vanes which were made by Vaisala. The measuring instruments were put on top of a mast at a height of 12.5 m above ground level or 15.3 m above sea level [16]. The wind data were collected for a period of 12 months from January to December in the year 2008. The data comprise the hourly mean wind-speeds and the directions [16]. After that, the analyses and the evaluation of the data were carried out. The monthly results were presented by using histograms and scatter diagrams. Besides that, the wind data also have been described by fitting the data into the Rayleigh distribution function. In addition, WPD was calculated, estimated and compared by using the bar plots for every month.

2.2. *Power law for estimates of wind-speed at various height*

As the meteorological station data are measured near to the surface and winds increase with altitude, the data should be calculated at turbine height [10]. Since the height of anemometer is 12.5 m above the ground, the wind-speed data are not suitable to predict the wind power potential at Penang Island at a higher altitude. In order to assess the wind energy at the height of 50 m, the power law has been use to estimate the wind-speed. The power law has received extensive application in the field of wind energy [17]. Basically, the power law equation can estimate the hub height wind-speeds at various potential sites [17]. Therefore, the wind-speeds at one height can be predicted in terms of the measured speed at another height by [17]

$$\frac{v_2}{v_1} = \left(\frac{z_2}{z_1}\right)^{\alpha} \quad (1)$$

where α is the power law exponent, v_2 is the extrapolated wind-speed at height z_2 and v_1 is the measured speed at z_1 from the ground level.

The exponent α depends on the several factors such as nature of terrain which including the surface roughness, wind-speeds and temperature [17]. According to Peterson and Hennessey [18], a power law exponent of 1/7 is adequate for realistic but conservative estimates of the available wind power. Furthermore, the exponent value of 1/7 has widely been chosen as a good representative of the prevailing conditions for neutral stability [18].

2.3. *Rayleigh distribution function of wind-speed*

Apart from the average strength of the wind over a period, the distribution is also a critical factor in wind resource assessment. The frequency distribution of the wind-speeds help towards answering questions of how long is a wind power plant out of action and how often does the wind power plant achieve its rated output [19]. It is logical to represent the wind velocity distributions by standard statistical functions. It is found that the Weibull and Rayleigh distribution function can be used to describe the wind variations in a regime with an acceptable accuracy level. However, the reliability of Weibull distribution in wind regime analysis depends on the accuracy in estimating shape factor, k, and scale factor, c. For the precise calculation of k and c, adequate wind data collected over shorter time intervals are essential. In many cases, such information may not be readily available. The existing data may be in the form of the mean wind velocity over a given time period, for instance, daily, monthly or yearly mean wind velocity. Under such condition, a simplified case of the Weibull model can be derived, approximating k as 2. This is known as the Rayleigh distribution [20].

The Rayleigh distribution function is derived from Weibull distribution function which is a special case of the Pierson Class III distribution. In the Rayleigh distribution function, the variations

in the wind velocity are characterized by two functions, PDF and CDF. According to Mathew [20], the PDF, $f(V)$, indicates the fraction of time for which the wind is at a given velocity, V, that can be express as

$$f(V) = \frac{\pi}{2}\frac{V}{V_m^2}e^{-[\pi/4(V/V_m)^2]} \tag{2}$$

where V_m is average wind speed of a regime [20]. The c value can be indicated how 'windy' the wind location under consideration is given by [9]

$$c = \left[\frac{1}{n}\sum_{i=1}^{n}V_i^k\right]^{1/k} = \frac{2V_m}{\sqrt{\pi}} \tag{3}$$

$$V_m = c\Gamma\left(\frac{3}{2}\right) \tag{4}$$

The most frequent wind-speed, V_f, can be determined by

$$V_f = \sqrt{\frac{2}{\pi}}V_m \tag{5}$$

Meanwhile, the CDF of the velocity gives the fraction of time that the wind velocity is equal to or lower than V. According to Mathew [20], the CDF, $F(V)$, is the integral of the PDF given by

$$F(V) = 1 - e^{-[\pi/4(V/V_m)^2]} \tag{6}$$

The probability of wind to exceed a velocity of V_x is given by [20]

$$P(V > V_x) = 1 - \{1 - e^{-(\pi/4)(V_x/V_m)^2}\} = e^{-(\pi/4)(V_x/V_m)^2} \tag{7}$$

2.4. WPD, air density and WED

Assessing the WPD available in the prevailing wind regime at a site is one of the preliminary steps in the planning of a wind energy project. WPD indicates how much energy per unit of time and swept area of the blades are available at the selected area for conversion to electricity by a wind turbine [3]. In order to get the most accurate estimate of WPD, the summation using data taken over a time interval was performed which is expressed as

$$\mathrm{WPD_{act}} = \frac{1}{2}\left(\frac{1}{n}\right)\sum_{i=1}^{n}\rho_i V_i^3 \tag{8}$$

where n is the total number of wind-speed reading, ρ_i is the ith reading of air density (kg m^{-3}) and V_i is the ith reading of the wind-speed in mean hourly basis (m s^{-1}). So, WPD takes into account the frequency distribution of the wind-speed and the dependence of wind power on air density and the cube of the wind-speed. Therefore, WPD is generally considered a better indication of the wind energy resource than wind-speed [9,12]. In this paper, the data have been analyzed using Matlab software which can cope with a huge and complex of data that including zero or low mean wind-speed. As a result, the arithmetic mean of WPD can be carried out and analyzed in an efficient way. Furthermore, by considering Rayleigh distribution, WPD can be expressed as [21]

$$\mathrm{WPD_{ray}} = \frac{3}{\pi}\rho V_m^3 \tag{9}$$

Meanwhile, the percentage error between the mean WPD can be found as

$$\text{Percent error} = \frac{|\mathrm{WPD_{act}} - \mathrm{WPD_{ray}}|}{\mathrm{WPD_{act}}} \times 100\% \tag{10}$$

WPD is proportional to the density of the air and to the cube of the wind-speed. However, air density is a function of temperature, T, and pressure, p, both of which vary with altitude above sea level, z. Therefore, whenever calculation regarding the wind potential at certain altitude, z, is performed, the corresponding air density, ρ, could be evaluated by

$$\rho = \rho_0\frac{T_0}{T}\left(1 - \frac{\Gamma z}{T_0}\right)^{(g/\Gamma R)} \tag{11}$$

where $g = 9.81$ m s^{-2} is the gravitational acceleration, $R = 287$ J deg^{-1} kg^{-1} is the gas constant, T is the temperature in K, $T_0 = 298$ K, $\rho_0 = 1.225$ kg m^{-3} is the standard sea level air density and Γ is the vertical temperature gradient [3]. In addition, estimation of wind power is based on the assumption that the density of air is not correlated with wind-speed. The error introduced by this assumption on a constant pressure surface is less than 5% [12,22]. Hence, in the current study, the air density is 1.225 kg m^{-3} for most of the practical cases [20].

One of important steps in assessing the wind potential of a selected site location is the WED that available in the wind regime. In addition, WED can be calculated once the WPD is known. WED is the energy available in the regime over a time period are usually taken as the yardsticks for evaluating the energy potential [20]. Meanwhile, WED shows how much energy is available at the site for conversion to electricity by a wind turbine [23]. As a result, WED is the energy available in the regime for a unit rotor area and time [20].

By considering Rayleigh distribution, total WED available that can be extracted in Penang Island can be calculated by

$$\mathrm{WED} = t\int_0^\infty P_V f(V)dV = t\int_0^\infty \frac{\pi\rho}{4V_m^2}V^4 e^{-[\pi/4(V/V_m)^2]} = \frac{3}{\pi}t\rho V_m^3 \tag{12}$$

where P_V is the power available in the wind stream for a unit of rotor and t is time period [20]. The equation can be used to calculate the available wind energy for any defined period of time when the wind-speed frequency distributions are for a different period of time which stated in [12].

3. Results and discussion

The determination of the wind potential of the selected site is made by analyzing in detail the wind characteristics, such as the wind-speed, their duration and availability as well as the resulting WPD. In this paper, the mean monthly and maximum wind-speed with 95% confidence interval has been plotted. The monthly mean hourly wind-speeds in three quarters for year 2008 from January until December on a 24-h basis also have been plotted. Then, Rayleigh distribution function of the wind-speed has been plotted for each month for 2008. In addition, the annual wind roses have been plotted based on the time and based on the energy. The monthly mean WPD and WED also have been plotted.

3.1. Mean monthly and maximum wind-speed

In Fig. 2, the mean monthly and maximum wind-speed with 95% confidence interval has been presented. The line segments are representing the confidence intervals. From the observation, the windiest month is in December that approximately 3.2 m s^{-1} while the calmest month is in May that solely 1.9 m s^{-1}. From the figure, the windy months are January, February, March, April, July, August, September and November. Those months have showed the mean monthly wind-speed that more than 2 m s^{-1}. Meanwhile, the calm months are June and October. The mean monthly wind-speeds of aforementioned calm months are below than 2 m s^{-1}. From the data collected, the annual mean wind-speed in 2008 was calculated based on the height of 50 m and it is around 2.34 m s^{-1}. As a result, a small scale wind turbine system could be installed and operated at Penang Island.

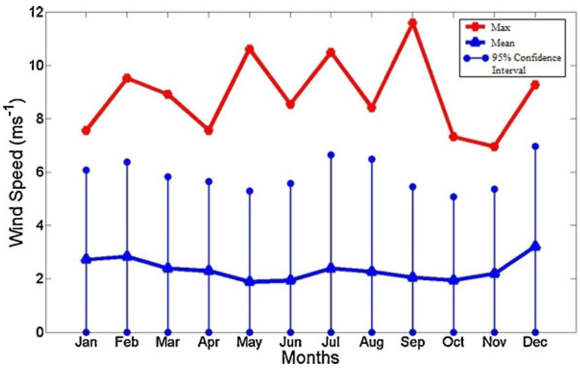

Fig. 2. Mean monthly and maximum wind-speed with 95% confidence interval.

By observing the trend of the mean monthly wind-speed in Fig. 2, the mean monthly wind-speed is increasing for May–July, and decreasing for July–October. Then, it increases from October to December and then decreases again from December to May. This typical change of climate in Penang Island is mainly due to two significant monsoon seasons, which are SW and NE monsoon seasons. The period of the SW monsoon season is started from May to September. At the same time, the NE monsoon season is starting to prevail in October and end of March.

Two of these monsoon seasons are basically describing the changes of the mean monthly wind-speed prevailing in Penang Island. The mean monthly wind-speed is increasing for May–July because of the starting of SW monsoon season taking place. It is believed that the peak prevailing of SW monsoon is in July. After that, the SW monsoon become weaker since the mean monthly wind-speed is decreasing for July–September. Then, it comes to the transition of monsoon season from September to October. On the other hand, the trends are showing that the mean monthly wind-speed is increasing from October to December. This phenomenon happened due to the NE monsoon season was blowing across the Penang Island. At the same time, since the windiest month is in December, it can be concluded that the peak prevailing of NE monsoon season at Penang Island also occurs in that month. The NE monsoon season is also showing the same characteristic compared to SW monsoon season. The NE monsoon season become weaker since the mean monthly wind-speed is decreasing from December to March. Then, the climate of Penang Island was underwent the transition of NE monsoon season to SW monsoon season whereby the mean monthly wind-speed is decreasing from March to May. As a result, the climate changes in Penang Island were generally covered by the NE and SW monsoon seasons.

Furthermore, the highest maximum wind-speed is achieved in the month of September with the approximate value of 11.6 m s^{-1}, while the lowest is in November that around 6.9 m s^{-1}. Moreover, the maximum wind-speed in May and July can be considered in higher maximum wind-speed range that is approximately 10.5 m s^{-1}, meanwhile, the maximum wind-speed in January, April and October are categorized in lower maximum wind-speed range which is around 7.5 m s^{-1}. Based on the trend, May, July and September have a higher value of maximum wind-speed because of the geographical location in Penang Island. During the SW monsoon season, it prevails from the sea shore to Penang Island without obstacle. The geographical location of Penang Island also making the lower maximum wind-speed occurs during January and November. Because of the existence of Peninsular Malaysia, during the NE monsoon seasons, most of the wind prevails from NE direction have been impeded. In addition, the maximum wind-speed in April and October are lower. This is mainly due to the transition period among those two monsoon seasons.

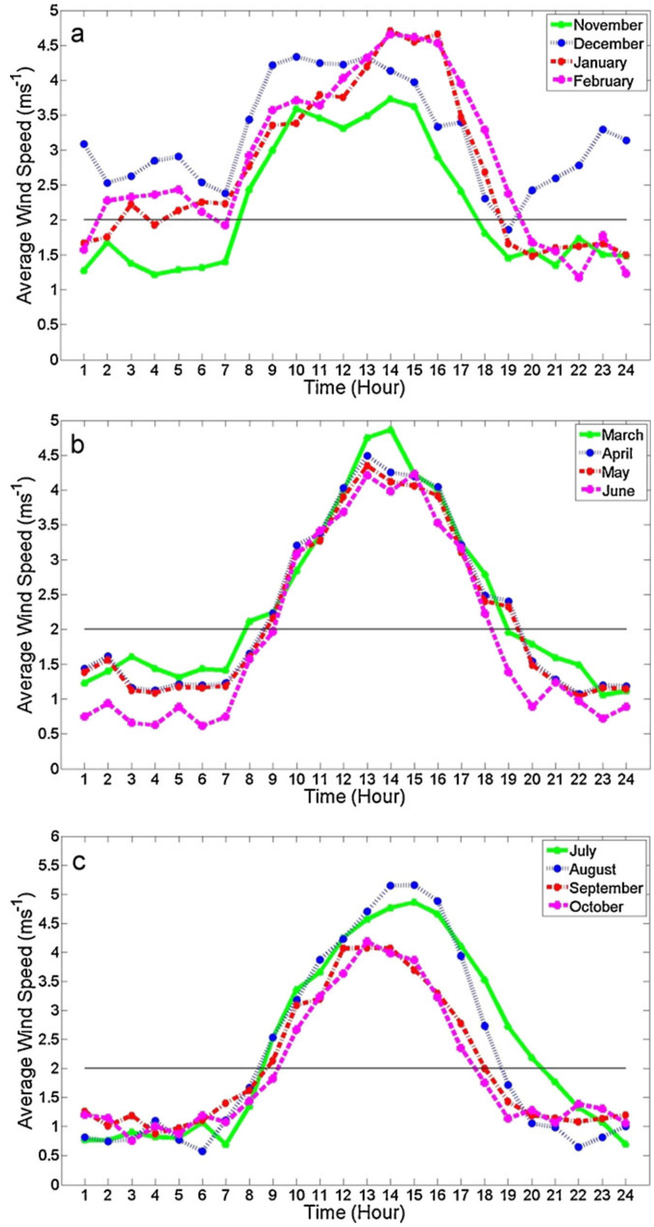

Fig. 3. Monthly mean hourly wind-speed in 2008: (a) November to February, (b) March to June, (c) July to October.

3.2. Monthly mean hourly wind-speed in three quarters

The monthly mean hourly wind-speed has been grouped for the three quarters comprising of four months in one quarter as shown in the three graphs in the Fig. 3. The wind-speed variations were plotted from November to February, March to June and July to October, respectively in the Fig. 3(a)–(c). Every point plotted in the graphs basically is the average wind-speed for every hour for each month. The horizontal line shows 2 m s^{-1} is used to compare the mean wind-speed which is more than 2 m s^{-1} or less than 2 m s^{-1}. The trends of the wind-speed variations in each quarter basically are almost similar as shown in the Fig. 3. The results show that during the day from 0700 until 1900 h, it is windy for all months, while at night, it is relatively calm which is including the zero or low wind-speed. The mean wind-speed also increases at around 0700 h and peaks at around 1400 h. Then, in the afternoon, the mean wind-speed is decreasing and goes to a low mean wind-speed at about 1900 h. Based on the observation, the daytime is windy for whole

Table 1
Monthly scale factor and most frequent wind-speed.

Month	V_f (m s^{-1})	c (m s^{-1})	%
January	2.26	3.19	67.51
February	2.36	3.34	69.91
March	2.08	2.94	63.00
April	2.00	2.83	60.79
May	1.79	2.54	53.71
June	1.88	2.66	56.71
July	2.26	3.19	67.57
August	2.19	3.09	65.84
September	1.88	2.66	56.84
October	1.76	2.49	52.51
November	1.91	2.70	57.75
December	2.63	3.71	74.83

year, while the night time is relatively calm. Thus, these trends show that having a higher mean wind-speed during day is better since the demand for energy is normally higher during day than at night.

The mean wind-speed above 2 m s^{-1} began from 0700 h until 1900 h as shown in the Fig. 3(a). At the same time, the mean wind-speed of more than 2 m s^{-1} started from 0900 h until 1900 h as seen in the Fig. 3(b) and (c). This is a normal phenomenon when a maximum speed occurs in the afternoon and the minimum speed occurs at night. A pattern is then controlled by convection in the surface boundary layer as the ground is heated by the sun during the day and cooled by radiation at night [7].

The peak mean wind-speed in January, February, March and July are almost 4.6 m s^{-1} while the peak mean wind-speed in August is approximately 5.2 m s^{-1} as shown in the Fig. 3. One of the reasons is that the NE monsoon begins from approximately October and lasts till March, while the SW monsoon starts from May and lasts till September. The mean wind-speed for the quarter from November to February is much higher than the other quarters because the NE monsoon blows more strongly than the SW monsoon in Penang. Meanwhile, the mean wind-speed is lower than 3.7 m s^{-1} all the time in November. In December, the mean wind-speed variation is more constant when compared to that of the other months. In addition, the mean wind-speeds which are more than 2 m s^{-1} can also be found at night.

3.3. Rayleigh distribution function of wind-speed

One of the important factors that need to be considered is the knowledge of a wind-speed distribution in order to assess the wind energy potential in Penang Island. Understanding wind characteristics requires a statistical tool such as Rayleigh distribution function. It can be used to fit the wind-speed data taken at the Bayan Lepas meteorological weather station. In addition, the calm wind-speeds including zero or low wind-speeds have also been analyzed using Rayleigh distribution analysis.

Analyses have been done monthly by plotting the Rayleigh distribution. Every Rayleigh distribution function consists of PDF and CDF. Every PDF of every month shows the scale factor, c, and also the most frequent wind-speed, V_f, parameters as listed in Table 1. Based on the table, the months with the scale factor that more than 2.8 m s^{-1} are January, February, March, April, July, August and December. These months also having the most frequent wind-speed that more than 2.0 m s^{-1}. Meanwhile, the other months having lower scale factor value and also the most frequent wind-speed. Furthermore, the windiest month which is in December, the scale factor and also the most frequent wind-speed are 3.71 m s^{-1} and 2.63 m s^{-1}, respectively. Opposite, the lowest value of scale factor and the most frequent wind-speed is occurring in the month of October which is 2.49 m s^{-1} and 1.76 m s^{-1}. On the other hand, the percentage of the wind-speeds those more than 2 m s^{-1} during the course of the year is dictated in Table 1 by using CDF. Based on the data, most of the months occupied more than 50% wind velocities that larger than 2 m s^{-1}. However, in October has the lowest content of higher wind velocity which is solely 52.51%. With the value shown, half of the wind velocities in October are low; hence, it is a calmest months. At the same time, the windiest month, December, exhibits a higher percentage of wind speed that is more than 2 m s^{-1} which is 74.83%.

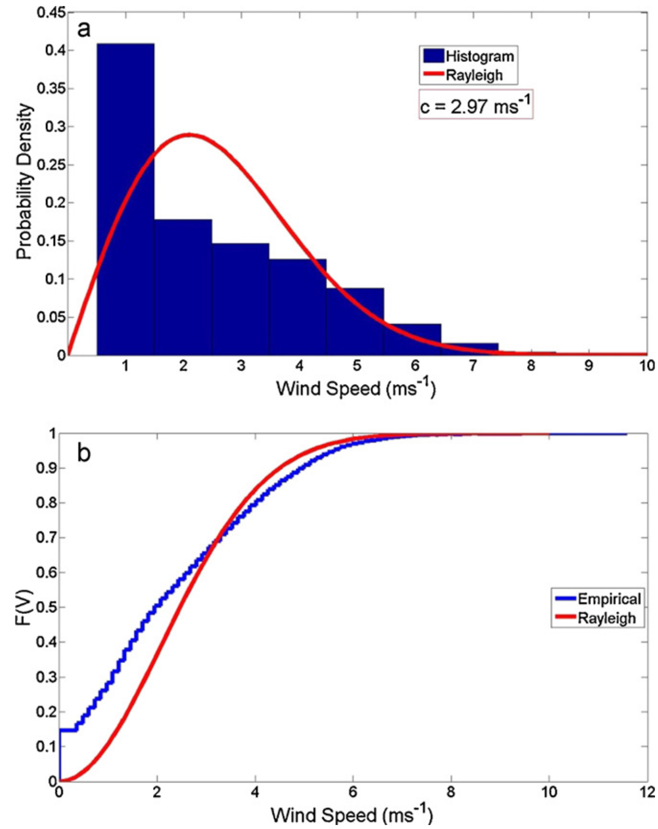

Fig. 4. Rayleigh distribution function of annually mean wind-speed: (a) PDF, (b) CDF.

Next, the annual mean wind-speed distributions also play important roles to be analyzed. The PDF shows that the c value is 2.97 m s^{-1} as shown in Fig. 4. Besides that, the most frequent wind-speed in Bayan Lepas is 2.10 m s^{-1}. The percentage of the mean wind-speed which is more than 2 m s^{-1} is about 64% of the mean wind-speed.

3.4. Wind direction

Besides the size and structure of wind-speeds, the direction of the wind is of decisive significant for the evaluation of the possibilities of utilizing wind power [19]. The prevailing wind becomes more crucial when planning the installation of a wind turbine generator. In this way, the wind rose has been plotted to predict the prevailing wind direction.

The annual wind rose frequency based on the time in 2008 is shown in Fig. 5. Most of the time, the prevailing wind in Bayan Lepas, Penang Island was from the N, north-northeast (NNE), SW and SSW directions. As can be seen, the highest percentage of the prevailing wind direction is 28% from the N. For the direction obtained earlier are 13% from the NNE and 7% from the SW and also 7% from the SSW directions. This phenomenon is predicted because the location is governed by the regime of the NE and SW monsoon which blow alternately during the course of the year.

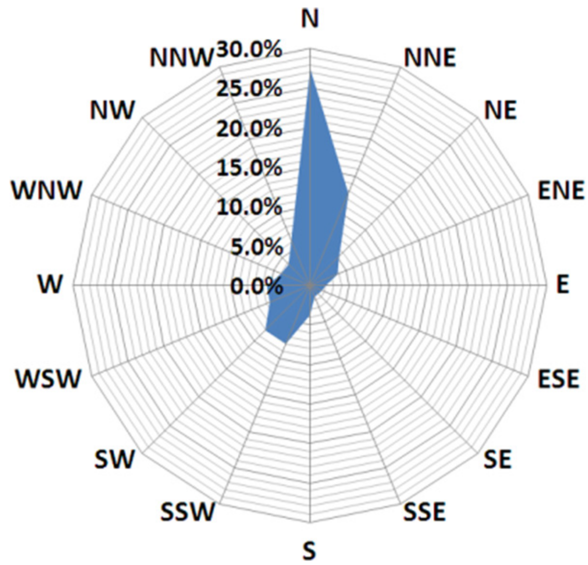

Fig. 5. Annual wind rose frequency based on the time.

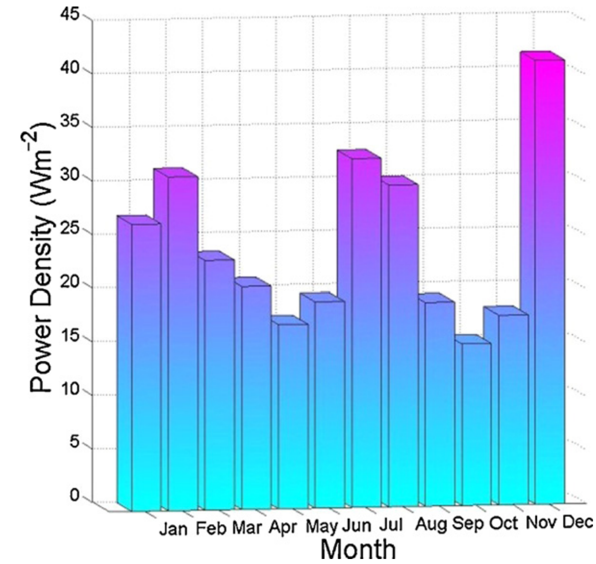

Fig. 7. Monthly mean WPD.

Instead of the prevailing wind direction, the wind direction that contributes different amounts of energy has also to be figured out. It is very significant when it comes to the installation of a wind turbine so that it can capture the maximum wind power available. The annual wind rose frequency based on the energy in 2008 has been plotted in Fig. 6. The directions that contribute higher energy are from the SSW, SW and WSW. As can be seen, the SSW direction has contributed the highest energy frequency which is about 17.5% from the overall occurrences. Their respective percentages are 16% from the SW, 9% from the WSW and south (S), 10% from the NE, 6% from the NNE and 8% from the ENE.

Furthermore, the wind rose shows that most of the wind prevails from N direction as indicated in Fig. 5. However, most of the wind that contributes higher energy is from NE direction as shown in Fig. 6. This is due to many lower wind-speeds flow into N direction. The location of Bayan Lepas which is situated at the East coast of Penang Island also causes this phenomenon happened. As a result, most of the wind prevails from the N direction has been hindered by Jerejak Island as well as Peninsular Malaysia. However, the shape of the wind roses as seen in Figs. 5 and 6 are slightly mismatched. The percentage of wind prevails in the SW direction based on time is small as shown in the Fig. 5. Nevertheless, the direction that contributes a higher energy frequency is from the SSW direction indicated in Fig. 6. This is because there are higher potential wind-speeds coming from the SSW direction.

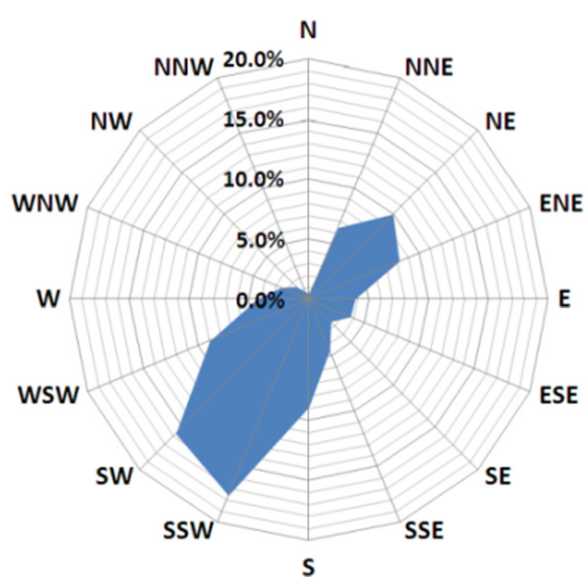

Fig. 6. Annual wind rose frequency based on the energy.

3.5. Mean WPD and WED analysis

Another important aspect is the evaluation of the mean WPD in Penang Island. Hence, the monthly mean WPD is plotted in Fig. 7. As can be seen, the higher mean WPD is in February, July, August and December which is more than 30 W m^{-2}. The highest mean WPD is in December which is about 42 W m^{-2} while the lowest mean WPD is in October which is about 15 W m^{-2}. There are significant differences of the mean WPD in December when compared to the other months because the wind blows in December almost constantly due to the NE monsoon in Malaysia. In addition, it is agreed the variations of the monthly mean hourly wind-speed from 0100 h until 2400 h in December which is almost constant as shown in the previous section. Then, in May, June, September, October and November, the mean WPD is lower than 20 W m^{-2}. Meanwhile, the mean WPD in January, March and April is between 20 W m^{-2} and 30 W m^{-2}. The annual mean WPD is 24.54 W m^{-2}. Consequently, it is considered to fall as a Class 1 wind category by refereeing to Table 2 [9].

It can be seen that the mean WPD in Fig. 7 starts to increase from May to June, then increases sharply to July and then it decreases gradually from July to October. It is believed that the wind is influenced by the SW monsoon. Then, the mean WPD begins to increase sharply from November to December, then it decreases to January gradually, and increases back to February. Next, the WPD trend is

Table 2
Wind power classifications for 50 m elevation.

Class	WPD (W m^{-2})	Wind-speed (m s^{-1})
1	0–200	0.0–5.6
2	200–300	5.6–6.4
3	300–400	6.4–7.0
4	400–500	7.0–7.5
5	500–600	7.5–8.0
6	600–800	8.0–8.8
7	More than 800	More than 8.8

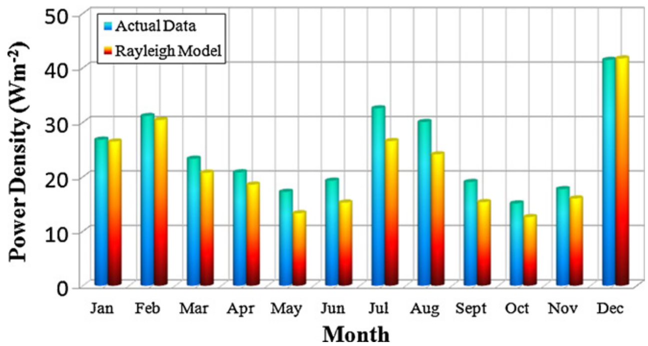

Fig. 8. Monthly mean WPD calculated from actual wind-speed data versus monthly mean WPD estimated using Rayleigh model.

to decrease slightly from February until May. It is also believed that the wind blows is influenced by the NE monsoon.

Fig. 8 illustrates the comparison between monthly mean WPD calculated using actual wind-speed and monthly mean WPD measured using Rayleigh model. The differences between both mean WPDs in January, February and December are very small, while the differences between both mean WPDs in other months are larger. The difference is observable because the wind speeds from months of March to November consist of low wind-speed as can be seen in Fig. 3. This could be the reason that Weibull distribution function is not applicable in this wind regime, therefore, Rayleigh model will return smaller error values in calculating the mean WPD. Besides that, the percentage error between monthly mean WPD is in the range of 0.67% and 20.91%. As indicated in [21], the highest error values of Weibull model and Rayleigh model are 22% and 35%, respectively. And so, the highest percentage error of monthly mean WPD estimated using Rayleigh model in Penang Island is much smaller than that of the Weibull model as indicated in [21]. In addition, the percentage error of estimating annual mean WPD in Penang Island shows only 11.36%, which is smaller than the error values of 13.0% that can be found in [21]. Hence, the wind data of this regime is properly fitted with Rayleigh distribution.

The other aspect that might be also important is the mean WED. The mean WED is estimated by using the formula (12). The monthly mean WED in 2008 is shown in Fig. 9. The trend of mean WED is the same as the trend of the mean WPD. As can be seen, the higher mean WED is in February, July, August and December which is more than 20 kWh m^{-2} month^{-1}. The mean WED in December is the highest mean WED which is about 31 kWh m^{-2} month^{-1} while the lowest mean WED is in October which is about 11 kWh m^{-2} month^{-1}. Then, in April, May, June, September, October and November, the mean WED is lower than 15 kWh m^{-2} month^{-1}. Meanwhile, the mean WED in January and March is between 15 kWh m^{-2} month^{-1} and 20 kWh m^{-2} month^{-1}. The figure shows considerable differences of the mean WED in December because a significant portion of the mean hourly wind-speeds which is more than 2 m s^{-1} recorded is during night. In addition, the annual mean WED is 17.98 kWh m^{-2} month^{-1}.

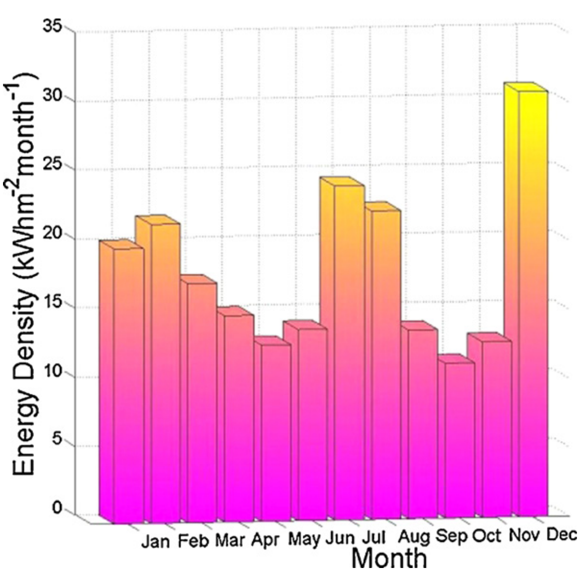

Fig. 9. Monthly mean WED.

4. Conclusion

From the data analyses, the results show that the measurement site at Bayan Lepas, Penang Island, Malaysia has a limited wind potential. The measurement site falls under a Class 1 wind classification. This area may not be an ideal site for large-scale electricity generation due to the cost factor, nevertheless, the utilization of wind energy in small-scale wind turbine generation applications still promising in the long run with the development of wind turbine technology. The windy months recorded are in January, February, March, April, July, August, September, November and December, meanwhile, the calms months are in May, June and October. This is highly influenced by the NE and SW monsoon seasons. Rayleigh statistical analysis has been applied to assess the wind energy potential in Penang Island that showing the scale factor value and the most frequent wind-speed in monthly and yearly basis. Besides that, most of the wind is the prevailing wind from the N and SW directions. However, the directions that contribute higher energy frequency are from NE and SSW. The mean annual WPD is estimated to be 24.54 W m^{-2}. The mean annual WED is estimated to be about 17.98 kWh m^{-2} month^{-1}.

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References

[1] Kreith F, Goswami DY. Handbook of energy efficiency and renewable energy. Boca Raton: CRC Press; 2007.
[2] Armstrong FA, Blundell KM. Energy... beyond oil. Oxford, New York: Oxford University Press; 2007.
[3] Fyrippis I, Axaopoulos PJ, Panayiotou G. Wind energy potential assessment in Naxos Island, Greece. Appl Energy 2010;87:577–86.
[4] Gokcek M, Genc MS. Evaluation of electricity generation and energy cost of wind energy conversion systems (WECSs) in Central Turkey. Appl Energy 2009;86:2731–9.
[5] Mostafaeipour A. Productivity and development issues of global wind turbine industry. Renew Sustain Energy Rev 2010;14:1048–58.
[6] Takahashi KOO, Arakawa H. Climates of southern and western Asia. Elsevier Scientific Pub. Co.: Amsterdam, New York; 1981.
[7] Sopian K, Othman MYH, Wirsat A. The wind energy potential of Malaysia. Renew Energy 1995;6:1005–16.
[8] Darus ZM, Hashim NA, Manan SNA, Rahman MAA, Maulud KNA, Karim OA. Potential of wind energy in sustainable development of resort island in Malaysia: a case study of Pulau Perhentian (Perhentian island). In: Proceedings of the 10th WSEAS international conference on mathematical methods, computational techniques and intelligent systems. 2008. p. 431–5.
[9] Mostafaeipour A, Sedaghat A, Dehghan-Niri AA, Kalantar V. Wind energy feasibility study for city of Shahrbabak in Iran. Renew Sustain Energy Rev 2011;15:2545–56.
[10] Cabello M, Orza JAG. Wind speed analysis in the province of Alicante, Spain. Potential for small-scale wind turbines. Renew Sustain Energy Rev 2010;14:3185–91.
[11] Jamil M, Parsa S, Majidi M. Wind power statistics and an evaluation of wind energy density. Renew Energy 1995;6:623–8.
[12] Keyhani A, Ghasemi-Varnamkhasti M, Khanali M, Abbaszadeh R. An assessment of wind energy potential as a power generation source in the capital of Iran, Tehran. Energy 2010;35:188–201.

[13] Zaharim A, Najid SK, Razali AM, Sopian K. Wind speed analysis in the east coast of Malaysia. Eur J Sci Res 2009;32:208–15.
[14] DOSM. Basic population characteristics by administrative districts. Putrajaya: Department of Statistics Malaysia; 2009, 5.
[15] ESMRD. Electricity supply industry in Malaysia: performance and statistical information. Kuala Lumpur: Energy Commission Malaysia; 2008.
[16] MMD. Climatological and hydrological section. Petaling Jaya, Selangor: Malaysian Meteorological Department; 2009.
[17] Kamau JN, Kinyua R, Gathua JK. 6 years of wind data for Marsabit, Kenya average over 14 m/s at 100 m hub height; an analysis of the wind energy potential. Renew Energy 2010;35:1298–302.
[18] Peterson EW, Hennessey Jr JP. On the use of power laws for estimates of wind power potential. J Appl Meteorol 1978;17:390–4.
[19] Pashardes S, Christofides C. Statistical analysis of wind speed and direction in Cyprus. Sol Energy 1995;55:405–14.
[20] Mathew S. Wind energy: fundamentals, resource analysis, and economics. Berlin, New York: Springer; 2006.
[21] Ali NC. Review of Turkey's current energy status: a case study for wind energy potential of Canakkale province. Renew Sustain Energy Rev 2011;15:2743–9.
[22] Hennessey JP. Some aspects of wind power statistics. J Appl Meteorol 1977;16:119–28.
[23] Mirhosseini M, Sharifi F, Sedaghat A. Assessing the wind energy potential locations in province of Semnan in Iran. Renew Sustain Energy Rev 2011;15:449–59.